Variations in geophone responses in temporary seismic arrays

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Introduction

Geophones with resonant frequencies of 1 to 4 Hz are commonly used short-period sensors for site response studies (e.g., Bonilla et al., 1997; Hartzell et al., 1997 and 2000; Frankel et al., 1999) and crustal reflection, refraction and tomography experiments (e.g., Brocher et al., 2001; Fuis et al., 2003). In many cases these studies require only accurate arrival time picks and not amplitude information, but site response and attenuation studies require accurate amplitude (ground velocity) data from these sensors. Furthermore, geophones are often used in these studies to record seismic phases at or below their nominal resonant frequency (e.g., Bonilla et al., 1997; Dutta et al., 2001; Hartzell et al., 2000; Pratt et al., 2003a).

For studies that require accurate ground velocity measurements or use a variety of sensor types, the instrument response must be removed from the data using either the manufacturer's specifications or results from geophone calibrations. Geophone placement, particularly any tilt to the sensor, can alter the instrument response significantly. The geophone response ideally is calibrated while the sensors are in the ground, but such *in situ* calibrations generally are not carried out because of time constraints. More commonly, it is simply assumed the geophones have the response characteristics specified by the manufacturer.

In a recent site response study in the Seattle area, named the Seattle Seismic Hazard Investigation of Puget Sound (Seattle SHIPS 2002; Pratt et al., 2003a), we used 72 three-component geophones from the Program for Array Seismic Studies of the

Continental Lithosphere (PASSCAL) instrument pool to determine the amplitudes of both horizontal and vertical ground shaking at sites over the Seattle sedimentary basin (Pratt et al., 2003a). During the experiment, we used the signal-coil calibration method (Rogers et al., 1995) to measure, *in situ*, the geophone response of all three components of each sensor (216 channels total). Also during these calibrations, ten geophones were calibrated twice without being disturbed. We subsequently calibrated all of the geophones immediately upon their return to the PASSCAL instrument center using the same calibration method.

Assuming that calibration tests give an accurate measure of the geophone response, the calibrations show the variation in geophone response that can be expected when installing sensors in a typical temporary deployment. Furthermore, the results answer the question of whether calibrations done in a laboratory can be used to correct the instrument response when the geophones are deployed. We conclude that the vertical component is relatively insensitive to the geophone placement, but *in situ* calibrations are mandatory if horizontal ground motions are to be known to within 10%. This is especially true for signals below the fundamental frequency, where the geophones showed large variations in response during a typical deployment.

The Seattle SHIPS Experiment

The Seattle SHIPS experiment (Pratt et al., 2003a) was designed to measure ground shaking above the 8-km thick Seattle sedimentary basin (Johnson et al., 1994; Pratt et al., 1997; Brocher et al., 2001). The basin is known to amplify seismic waves in the 0.01 to 7 Hz frequency range (Frankel et al., 2003; Pratt et al., 2003b; Barberopoulou et al., 2004). In the experiment, we maintained a 110 km by 70 km array of 87 three-component seismometers over the Seattle basin and surrounding areas from late January to May, 2002.

We used Mark Products geophones in the Seattle SHIPS experiment, but we focus on the general issue of how a standard field deployment affects the sensor response rather than testing a specific geophone model. We anticipate that the results presented here would be similar had we used other makes and models of geophones. We used 72 identical Mark Products 3-component, L-22 geophones, supplemented by 15 L-22 geophones owned by the U. S. Geological Survey (USGS). The USGS geophones are not included in this report because they had different damping resistors than the IRIS sensors, and thus different response characteristics. The L-22 geophones have a fundamental resonance frequency of 2 Hz, and all 3 components are packaged in a single, cylindrical shell with a height of 14 cm and a diameter of 18 cm. The wire connector extends from one side of the cylinder, and there is a handle and a small bubble level on top. These bubble levels can be difficult to read when dirty and placed at the bottom of a hole, so the deployers also carried a separate bubble level that could be placed on top of the geophones when they had difficulty reading the one built into the case.

Our deployment method was typical for a site response study. A hole was dug in soil to depths of 0.3 to 0.8 m, some loose soil was placed in the bottom of the hole and tamped to make it level, and the geophone was placed on this dirt. Geophones were oriented with the first horizontal component aligned to magnetic north. A bubble level was used to ensure the geophones were level, with additional dirt being placed beneath the geophone or the side of the geophone being pushed downward to make it level. The hole was then filled with dirt that was gently tamped into place, and then tamped relatively hard when the entire hole was filled. The geophone was thus level when the hole was filled, and deployers were warned to not displace the geophone when filling the hole, but we do not know whether the geophones were tilted slightly during this filling process. Conditions were generally wet for the duration of the study, as light rains are characteristic of winter and spring weather in Seattle. We estimate that the geophones were equilibrated to the average Seattle winter and spring temperatures of 40˚F to 50˚F when the *in situ* calibrations were carried out.

Signal Coil Calibrations During the Seattle SHIPS Experiment

We calibrated all of the geophones in the Seattle SHIPS experiment using the signal-coil method of Rogers et al. (1995) as implemented by PASSCAL. This method consists of applying a current step (0.02 to 0.03 milliAmps) to the geophone signal coil to displace the mass to one side. The current is applied for several seconds to ensure the mass is at rest in its new position, and then the input current is stopped, allowing the mass to return to its rest position. The output pulse from the geophone is recorded as the mass returns to its equilibrium position. This effectively is the same method that was used previously to calibrate a subset of PASSCAL geophones (Menke *et al.*, 1991). Figure 1a shows a typical geophone calibration pulse resulting from this process.

To determine the geophone response, a best-fitting model is matched to the recorded pulse (Fig. 1a). The geophone's resonant frequency (f_0), fractional damping ratio (ζ) and damped generator constant (G_d) are determined from the model pulse, whose shape is defined by these three parameters. Repeating this process for each direction (positive and negative initial deflections) for each component results in 6 individual responses for each 3-component geophone. The results from the two directions for each component are averaged, and the velocity sensitivity (*VS*) is computed from the equation (Aki and Richards, 1980):

$$|VS(\omega)| = \frac{G_d \omega^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + 4\zeta^2 \omega_0^2 \omega^2}} \qquad (1)$$

where $\omega = 2\pi f$ and $\omega_0 = 2\pi f_0$.

After deployment, we let the geophones equilibrate for two weeks before beginning our *in situ* calibrations. The calibrations were made intermittently by one person over a 3-month time period during 11 separate days of field work. The results of these calibrations are contained in a table in Pratt et al. (2003a), and the calibration pulses are included with the experiment's data archive at the Incorporated Research Institutes for Seismology (IRIS) Data Management System (DMS; www.iris.edu).

After the geophones were returned to the IRIS instrument center in Socorro, New Mexico, they were calibrated in the laboratory in a single day. These laboratory calibrations were made using the same calibration instrumentation and software as was used for the *in situ* calibrations. For the laboratory calibrations, the geophones again were placed on a level lab bench, although the geophones were not oriented geographically in a strict manner. The two sets of calibrations are therefore representative of what might be carried out routinely during a seismic experiment. In addition to being moved and shipped, there were two major differences between the laboratory and *in situ* calibrations: 1) the *in situ* temperature was 40˚F to 50˚F as opposed to about 70˚F in the lab, and 2) the geophones were oriented to magnetic north in the field but were not systematically oriented in the lab.

The calibration process, as implemented by PASSCAL at the time of the experiment (2002), had two major pitfalls. The first is that the process relied on field file numbers, site numbers, sensor numbers, resistances and input current values being written down in the field, and later being typed into the computer for the calibrations. The resistances and currents are matched with the appropriate calibration pulse by typing them in the correct sequential order. This data input method, which requires writing down and then typing 11 numbers per geophone in the correct order (including geophone number and site number), opens the possibility of incorrectly writing or mistyping numbers, or incorrectly sequencing the calibration pulses.

The second major calibration error is clipping of the calibration pulses. The input electric current used to pull the mass to one side must be large enough to overcome noise levels, but small enough to prevent the mass from reaching its limit or causing clipping in the recorder. About 40% of our *in situ* calibration pulses showed evidence of clipping, which we discovered too late in the experiment to correct. In most cases, the very top of the output pulse was slightly truncated but the model calibration pulse closely matched the recorded calibration pulse (Fig. 1b). In these cases of minor truncation, we assumed that the calibration is accurate. In some cases the pulse was badly truncated, resulting in the sides of the model pulse deviating significantly from the observed pulse (Fig. 1c). In these cases, we tried to repeat the *in situ* calibrations, but this was not possible at all sites because some were removed before we processed the calibration data. In the laboratory we repeated the calibration using a smaller input current. If geophones had one badly clipped channel, or did not produce a reasonable calibration pulse (malfunctioning channel), we removed that component from our analysis but still used the calibrations from the remaining components if they did also not suffer from these problems. After this selection, the data set consisted of 60 geophones that had at least 2 components correctly calibrated both *in situ* and in the lab.

In the case of slight clipping we used the calibration pulse under the assumption that the resulting model pulse was unaffected. Comparing averages using the correctly recorded pulses and slightly clipped pulses (Table 1), it appears that slight clipping possibly reduced the measured resonant frequency (f_0) and increased the measured damping (_). However, the laboratory calibrations, none of which were clipped, also showed an average damping that was greater than the manufacturer's specification (Table 1). For the generator constant, slight clipping did not show a consistent bias. As we discuss later, our average values for f_0 were consistently higher than the manufacturer's specifications, so using the slightly truncated pulses may have reduced the discrepancy between the observed and design values of f_0.

Consistency of the Calibration Method

We can estimate the consistency of the calibration process by comparing two sets of calibrations from ten geophones (all 3 components) that were calibrated twice *in situ* without being moved. All of our repeat calibrations agreed to within 5% (Fig. 2). Rogers et al. (1995) reported that results of the signal-coil method are within 3% of the results from two other calibration methods, and within 3% of the manufacturer's specifications. Our results confirm the consistency of the calibration method to within a slightly greater value of 5% (Fig. 2). The calibration results are thus repeatable, although we did not use other calibration methods to confirm that the results are giving the true values. We therefore cannot determine if the results are biased, for example, by inaccurate input calibration current levels or during the computer matching of the model calibration pulse to the observed calibration pulse.

Average Calibration Values

Table 1 compares the nominal manufacturer's specifications with the average results of our calibrations for the resonant frequency, generator constant and damping. The calibration results are computed by averaging all values from both sets of calibrations. After removing badly truncated pulses, our final values are the average of the results from 792 individual calibration pulses.

The average resonant frequency of the geophones we tested was 2.078±.21 Hz, or about 3.9% higher than the manufacturer's nominal specifications (Table 1). This close to the value of 2.1±0.15 Hz determined in earlier tests (Menke *et al.*, 1991). The damped generator constants averaged 90.451±4.89 V/m/sec, or about 2.8% higher than the manufacturer's specification (Menke et al. [1991] only states that his values were within manufacturer's specifications). The damping in our tests averaged 0.739±.094% of critical, about 3.5% higher than the manufacturer's specification (Menke *et al*. [1991] determined 0.7±0.1). All three channels showed similar average values for all three parameters. Although these differences are within the 5% estimated error of the calibration process, a large-sample test indicates that the average is statistically different from the manufacturer's specifications. However, the geophones are, on average, well within the manufacturer's stated variance of ±10% of the design values.

Looking at the *in situ* and laboratory calibrations separately, both sets of calibrations show the geophone frequency, generator constant, and damping to be several percent higher than the manufacturer's specifications (Table 1). Again the differences are statistically significant, according to the critical ratio test, but are well within the manufacturer's tolerances.

Ultimately we want to know the velocity sensitivity of the geophone to convert to ground motion, so figure 3 shows a graph of the geophone velocity sensitivity computed from equation (1) using the manufacturer's specifications and using the averages of our calibration results. All three of our calibration test averages (total, *in situ*, laboratory) result in nearly identical geophone response curves that differ slightly from the velocity sensitivity computed from the manufacturer's specifications. Below about 4 Hz (twice the nominal resonant frequency), our calibrations indicate that the recorded ground velocities are as much as 7% lower than expected from the manufacturer's specifications.

Above 4 Hz our average calibration indicates recorded ground velocities are up to 2.4% greater (Fig. 3).

Variations between geophone responses

Looking at the response of individual geophones in the field during the SHIPS experiment gives us an idea of how the geophone placement affects the response. To summarize our results, both sets of our calibrations show less variation among the vertical components than among the horizontal components, and the damped generator constant shows less variation than the fundamental frequency and damping.

Figures 4 through 6 summarize the calibration results for fundamental frequency (Fig. 4), damped generator constant (Fig. 5) and damping (Fig. 6) for the 60 geophones. Each figure contains 3 graphs showing the calibration results for each component of the geophones. Within each graph, the percent differences between the manufacturer's specifications and each of our calibrations are shown as open squares and diamonds, and the percent differences between our two sets of calibrations are shown as filled circles.

Examining these graphs (Figs. 4-6), the most noticeable trend is that the vertical component shows considerably less variation between geophones in frequency (Fig. 4) and damping (Fig. 6) in both sets of calibrations than do the horizontal components. The horizontal components show variations of 40% or more in the frequency (Fig. 4) and damping (Fig. 6) on both of our calibration sets, and also up to 40% differences between the *in situ* and laboratory calibrations. We interpret these results as showing that the frequency and damping are extremely sensitive to the geophone placement, resulting in substantial differences between individual geophones and between the two calibrations of the same geophone. Given that each direction of the horizontal components nearly always had different calibration values, we suspect that the differences are largely the result of the geophones being slightly tilted despite the use of a bubble level during the deployment. The vertical component has less variation between geophones (see below), consistent with it having less sensitivity to tilt angle. The damped generator constant also appears to be relatively insensitive to the geophone placement.

Both calibrations of the vertical components show they lie within 20% of the manufacturer's specifications for all 3 parameters for nearly all of the geophones, with only 17% of the geophones showing **any** value more than 20% off specification. The results from the *in situ* and laboratory calibrations likewise lie within 10% of each other for nearly all of the geophones, with only 7% of the geophones having differences of more than 20% between calibrations. The vertical-component values for an individual geophone were consistently high or consistently low in both sets of calibrations, indicating some correlation between calibration tests. This correlation suggests that laboratory calibrations done before or after a deployment will improve the accuracy of amplitude measurements on the vertical component, though not as well as *in situ* calibrations.

The damped generator constant also showed little difference from specification for most geophones (Fig. 5), regardless of channel. Most (77%) of the geophones had generator constants within 10% of specification, and only three (1%) had values that deviate more than 20% from specification.

Geophone velocity sensitivity

The differences between individual geophone calibration parameters (frequency, generator constant, damping) do not directly indicate the differences in the measured velocity, as it is the combination of these 3 parameters that determine the overall geophone response (equation 1). When the geophone velocity sensitivities are computed using equation (1), there is considerably less variation than might be expected given the substantial differences in the frequency and damping.

Figures 7 through 9 show the measured geophone velocity sensitivity (in V/m/s) for each component at frequencies of 0.5, 1.0, 2.0 and 8.0 Hz, computed from equation (1) using our calibration results. Table 2 gives the average sensitivities, and the standard deviation of the percent difference between the measured geophone responses and the specifications; in other words the standard deviations of the points plotted in Figures 7-9. Figure 10 plots these standard deviations. These values presumably also represent the variation in geophone response that can be expected in an experiment, with the calibrations presumably removing this variation.

The percent differences in the geophone velocity sensitivities measured in both sets of our calibrations increase dramatically at frequencies below the 2 Hz fundamental frequency of the geophones. At 8 Hz and 2 Hz, only 8% of the geophones had velocity sensitivities (any component) that differed by more than 20% from manufacturer's specifications (Fig. 7-10), with the standard deviations being 4.0% to 6.1% (Fig. 10; Table 2). These standard deviations are near the 5% accuracy of the calibration method. The standard deviations are well within the manufacturer's stated 10% variance, but individual geophones apparently do fall outside the 10% variance when installed in a typical experiment.

At frequencies below the resonant frequency of the geophones, the velocity sensitivities determined in both sets of our calibrations differ significantly from the manufacturers' specification and between the two sets of calibrations. At 1 Hz and 0.5 Hz, the vertical component shows geophone sensitivities more than 20% different from the specification for 27% of the geophones (Fig. 7), and the standard deviation of the differences rises to nearly 10% (Fig. 10; Table 2). Significantly, the two calibrations of the vertical component are within 10% of each other for 90% of the geophones, and figure 10 shows that at 0.5 Hz the standard deviation of the difference between the two calibrations is less than that of the differences from specification. These standard deviations indicate a correlation between the lab and *in situ* calibrations, meaning that calibrations of the vertical component done in the laboratory before or after deployment will at least partially correct the geophone during field experiments.

The horizontal components, however, show large variations in geophone response at 1 Hz and 0.5 Hz, with differences greater than 20% from specification being common (Figures 8-10). Standard deviations are 15% to 23% for the velocity sensitivity of the horizontal component at 0.5 and 1 Hz. It is unrealistic to think that minor changes in the deployment method could correct these differences, as all of the geophones already had been leveled with a bubble level before these calibration tests. More accurate installation procedures would be time-consuming. For example, more accurate leveling of the geophones could be accomplished by equalizing the calibration for both polarities of each horizontal channel, or the geophone could be better held level by setting it in plaster at the bottom of the hole or gluing the geophones to concrete pads. For small numbers of installations these procedures could be used, but they are too time-consuming for arrays involving large numbers of geophones like we used in the Seattle SHIPS experiment.

The two sets of horizontal-component calibrations also show differences of greater than 20% for many of the geophones, and standard deviations of the differences between calibrations of greater than 20% (Fig. 10), suggesting little correlation between lab and *in situ* calibrations. These results are consistent with the variation between geophones primarily being the result of the different geophone placements rather than being a characteristic of the individual instruments. Clearly, *in situ* calibrations are needed to determine horizontal ground velocities to within 10% of the correct value at frequencies at or below the resonant frequency.

Differences between in situ and laboratory calibration tests

The previous plots indicate that *in situ* calibrations are needed for accurate velocity determinations, at least on the horizontal channels at frequencies at or below the fundamental frequency of 2 Hz. We further examine this issue by plotting the *in situ* and laboratory calibrations against each other. Figure 11 shows graphs of the fundamental frequency, damped generator constant and percent damping determined for the individual geophones in the two sets of calibrations. As indicated in Figures 4-6, the vertical component values derived from the two sets of calibrations lie within 10% of each other for most geophones. Likewise, the damped generator constant is consistent for all three components to within 10% between the two calibrations for nearly all of the geophones, with only 8% of the values differing by more than 10%.

The frequency and damping of the horizontal components, however, show large differences between the two sets of calibrations. About 16% of the geophones showed differences of more than 10% in the measured fundamental frequencies on the two sets of calibrations, and about 42% of the geophones had damping values that differed by more than 10%. These differences are presumably due to factors such as the tilt and temperature that differ from site to site.

Figure 12 shows the differences in the geophone sensitivity determined from the two sets of calibrations. At 8 Hz, the two calibrations for all components lie within 10% of each other for 96% of the geophones. There is slightly more scatter at 2 Hz, but 92% of the geophones still show lab and *in situ* calibrations within 10% of each other for all components. For the vertical component, the two calibrations show a good correlation at the lower frequencies as well, with 90% of the calibrations lying within 10% of each other. Unfortunately, there are enough exceptions that 10% accuracy cannot be assumed for every geophone during an experiment.

The geophone response computed for the horizontal components below the 2 Hz resonant frequency shows substantial differences between the *in situ* and laboratory calibration tests (Fig. 12, lower graphs). A sizeable fraction (45%) of the calibrations show differences greater than 10% between the two sets of calibrations. It is thus clear that *in situ* geophone calibrations are required to measure horizontal ground velocities to within 10% below the fundamental frequency of 2 Hz.

Discussion

In the Seattle SHIPS 2002 experiment, the calibrations made significant differences in the computed spectral amplitudes, particularly for signals below the fundamental frequency of the geophones. After calibration, the spectral ratios showed a more uniform response with less variation between nearby sites. The differences in the geophone responses suggest that much of the variation between adjacent sites that we saw in previous experiments could be due to instrument response. For example, the 1999 SHIPS experiment had a linear array across the Seattle basin that showed an overall 10 to 16-fold amplification of low-frequency (0.3 Hz) waves by the Seattle basin, but the data also showed variations of up to 20% in spectral amplification at adjacent sites a few km apart (Pratt et al., 2003b). The Mark Products L-28 geophones used in the 1999 experiment were not calibrated, but we suspect those geophones would show a similar variation as we document here for the L-22 geophones. If so, the ±20% amplitude differences between adjacent sites in the 1999 experiment could be due in large part to variations in instrument response rather than being a true measure of the site response. The overall pattern of basin amplification seen in the 1999 SHIPS experiment still holds, as the amplification is a factor of 5 times larger than the geophone variations, but amplitude differences of 20% between adjacent sites may not be meaningful. Unfortunately, the ~20% variations in the horizontal geophone responses between our two calibrations tests indicate that there is no accurate method for calibrating the geophone response at a site once the geophone is removed.

We have not examined the phase of the geophones as determined by our calibrations, because we were not concerned with the precise arrival times. We suspect there would be a similar variation in the phase, and that field calibrations would be needed to precisely determine the phase of low-frequency signals recorded by the L22 geophones.

One aspect of the calibration method that needs to be investigated is computing the response of each component by averaging the results from displacements of different polarity. Menke *et al.* (1991) noted a discrepancy between the two directions of motion of each component, and they suggest this is due to a non-linear behavior in the spring.

Specifically, they hypothesized that the spring had different characteristics under compression than under extension. We cannot resolve the cause of this discrepancy, but we point out that averaging the two directions of motion during the calibrations is based on the assumption that motions in both directions are contributing equally to the output signal. However, it is possible that one direction of motion contributes more than the other if the geophone is tilted, because the spring would be compressed in one direction when the geophone is at rest.

Conclusions

Calibrations of 60 geophones during the Seattle SHIPS seismic experiment demonstrate that *in situ* calibrations are necessary to ensure determinations of ***horizontal*** ground velocities to within 10% of their true values. The calibrations show that variations in horizontal geophone response of up to 20% are common in standard seismic experiments at frequencies above the resonant frequency of the geophone, and as much as 40% at half the resonant frequency. Individual geophones are not consistent between *in situ* and laboratory calibration tests, indicating it is the geophone placement that causes these variations and that the calibrations must be done *in situ.* Repeat calibrations of 10 different geophones indicates the signal-coil calibration method gives results that are consistent to within 5%, implying that calibrated geophones are accurate to about 5% in a typical experiment.

The *in situ* and laboratory calibrations show that the velocity sensitivity of the ***vertical*** component in a typical deployment can be expected to lie within 10% of the manufacturer's specifications for most geophones, but a small number of exceptions means that this accuracy cannot categorically be assumed. There was some correlation between the velocity sensitivities determined by the *in situ* and laboratory calibrations of the vertical component, suggesting that calibrations done before a deployment will at least partially correct the ground velocities measured on the vertical component.

The results of our *in situ* and laboratory calibrations of 60 PASSCAL, three-component L-22 geophones indicate a slight discrepancy from the manufacturer's specifications, with the average fundamental frequency, damped generator constant, and damping all being 1.5% to 7% higher than the specifications. These results suggest that the ground velocities measured in a typical field experiment will, on average, be slightly (2.4%) greater than the true values at frequencies more than twice the resonant frequency, but as much as 7% less than the true values at lower frequencies.

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Table 1: Manufacturer's specifications versus average of calibrations and the effects of slight clipping on our *in situ* calibrations

Parameter	Spec	Calibration	Std. Dev.	% Diff
Values using only unclipped pulses:				
f_0 (Hz)	2.0	2.184	0.558	9.2
G_d (V/m/sec)	88.0	88.781	7.727	0.9
_ (% critical)	0.707	0.705	0.099	-0.3
Values using only slightly clipped pulses:				
f_0 (Hz)	2.0	1.989	0.162	-0.5
G_d (V/m/sec)	88.0	92.868	5.921	8.9
_ (% critical)	0.707	0.770	0.051	1.9
Values using only badly clipped pulses:				
f_0 (Hz)	2.0	1.841	0.147	-8.0
G_d (V/m/sec)	88.0	90.98	2.787	3.4
_ (% critical)	0.707	0.787	0.058	11.3

Parameter	Spec	Calibration	Std. Dev.	% Diff
All calibrations:				
f_0 (Hz)	2.0	2.078	0.208	3.9
G_d (V/m/sec)	88.0	90.451	4.890	2.8
_ (% critical)	0.707	0.739	0.094	3.5
In-lab calibrations:				
f_0 (Hz)	2.0	2.031	0.180	1.6
G_d (V/m/sec)	88.0	90.945	4.726	3.3
_ (% critical)	0.707	0.755	0.100	6.8
In situ calibrations:				
f_0 (Hz)	2.0	2.133	0.226	6.6
G_d (V/m/sec)	88.0	89.883	5.026	2.1
_ (% critical)	0.707	0.720	0.082	1.9

Table 2: Velocity sensitivity by component and channel

Comp.	………………………………Geophone Sensitivity…………………………							
	0.1 Hz		1.0 Hz		2.0 Hz		8.0 Hz	
	ave	stdev (%)	ave	stdev (%)	ave	stdev (%)	ave	stdev (%)
V	5.2	9.4	20.0	8.4	59.0	6.1	90.4	5.1
H1	5.2	19.6	20.0	15.4	59.1	5.5	89.9	4.0
H2	5.5	23.2	20.6	15.0	58.7	6.0	89.3	5.0

Table 2: For each component, the table shows the average geophone sensitivity (ave), and the standard deviation of the percent error between the measured values and the manufacturer's specifications (stdev %). The latter is an estimate of the variation in amplitude to be expected when recording waves of that frequency with different L-22 geophones.

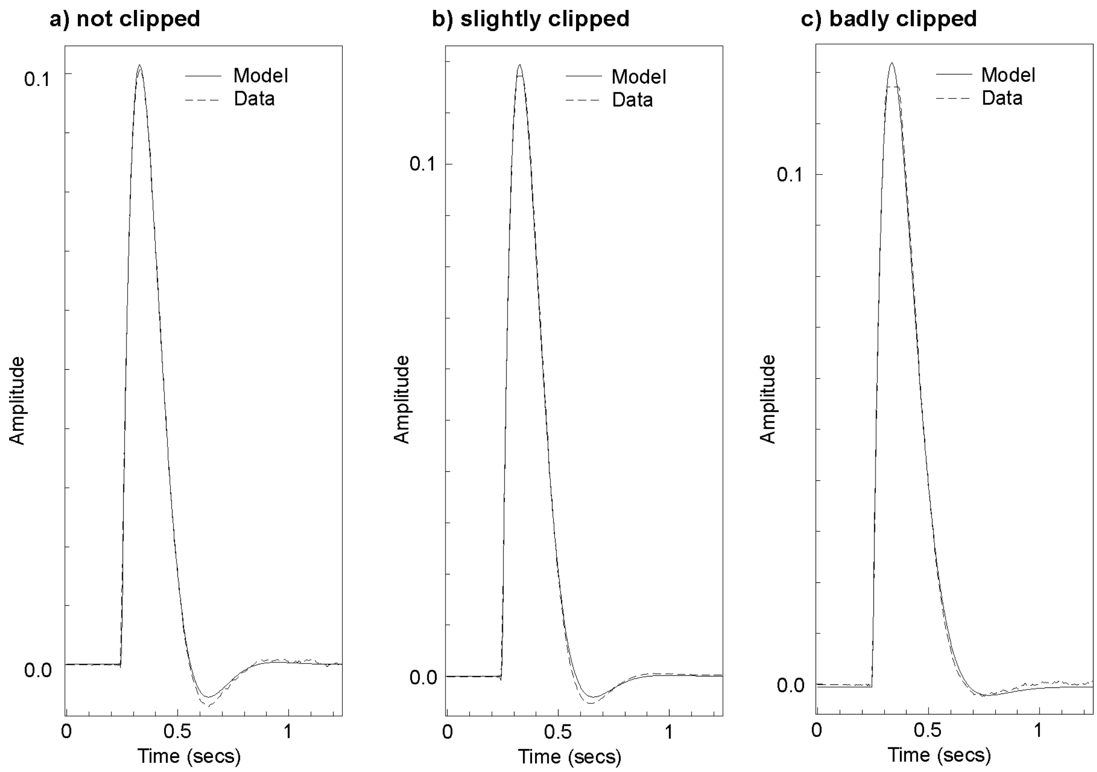

Figure 1: Examples of calibration pulses from the Seattle SHIPS experiment, and the best-fit models from the calibration software. Slightly overdriven pulses (b) have not been so distorted as to have a significant effect on the model pulse. Badly overdriven pulses (c) are so distorted that the model pulse does not match the remainder of the pulse.

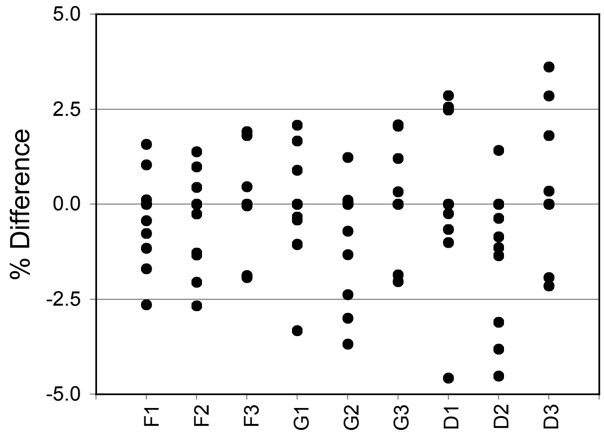

Figure 2: Comparison of pairs of calibrations from the 10 geophones that were calibrated twice without being disturbed. Abbreviations F1-D3 represent frequency (F), generator constant (G) and damping (D) coefficients for the vertical (1) and two horizontal components (2 and 3). Dots represent the percent difference between a parameter (F1-D3) as determined by two *in situ* calibrations of the same geophone. Channels having all zero amplitudes or with clipped pulses were removed.

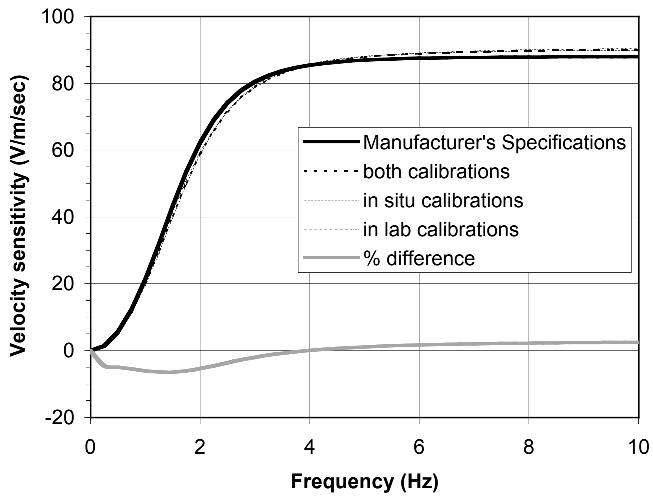

Figure 3: Comparison of geophone velocity sensitivity using (1) manufacturer's specifications, (2) the average of both of our sets of calibrations, (3) the average of our *in situ* calibrations, and (4) the average of our laboratory calibrations. Our averages give nearly identical results that differ slightly from the manufacturer's specifications. The gray line represents the difference, in percent, between the geophone sensitivity determined from the manufacturer's specifications and from the average of all of our calibrations.

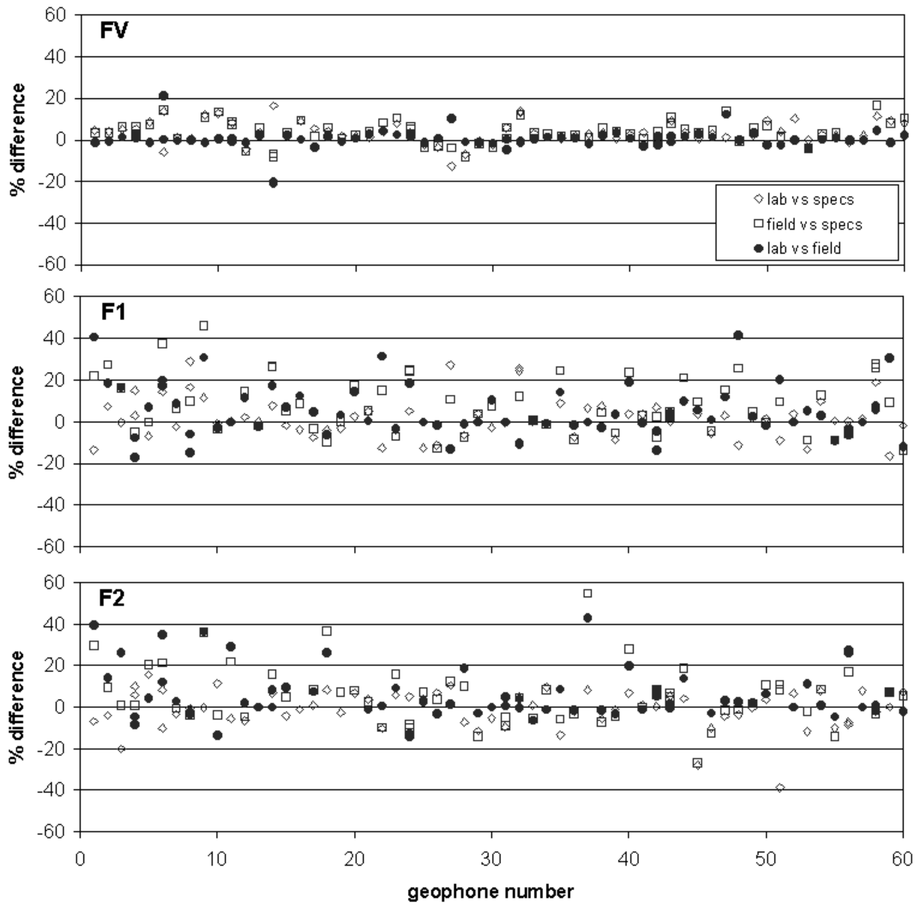

Figure 4: Percent differences in fundamental frequency (F) of L-22 geophones compared to manufacturer's specifications and between our two sets of calibrations. Results are shown for the vertical (top) and two horizontal components (middle and lower).

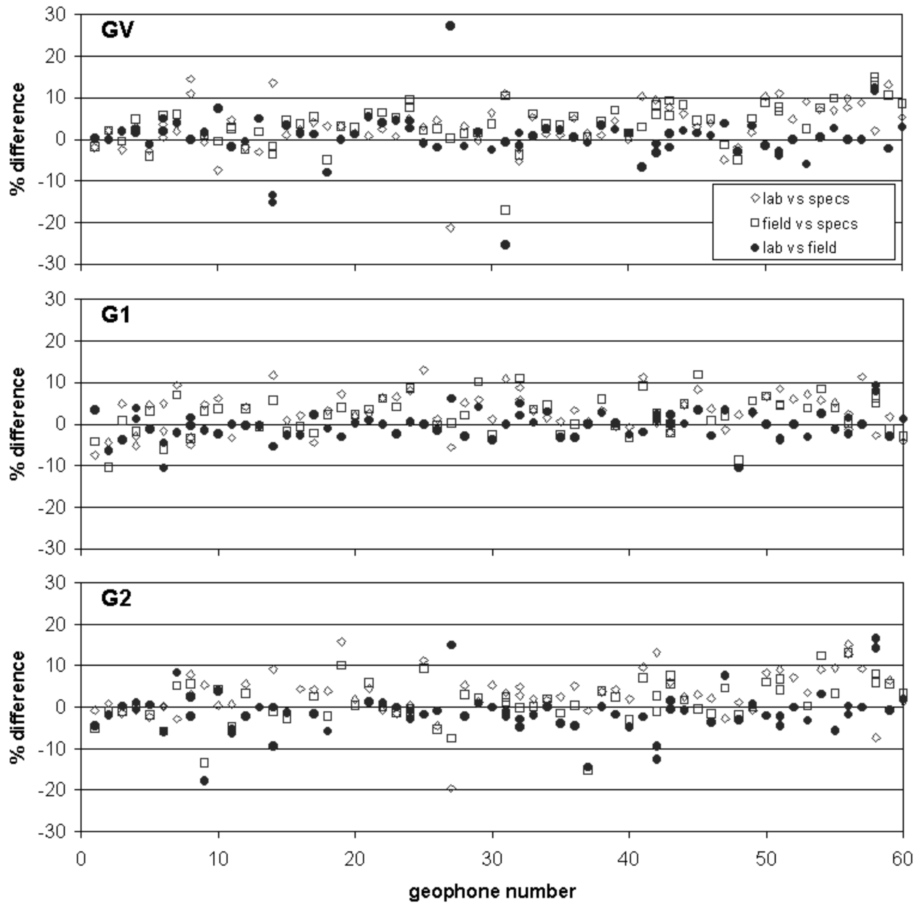

Figure 5: Percent differences in the damped generator constant (G) of the L-22 geophones determined from our calibration tests. Symbols and plots as in figure 4.

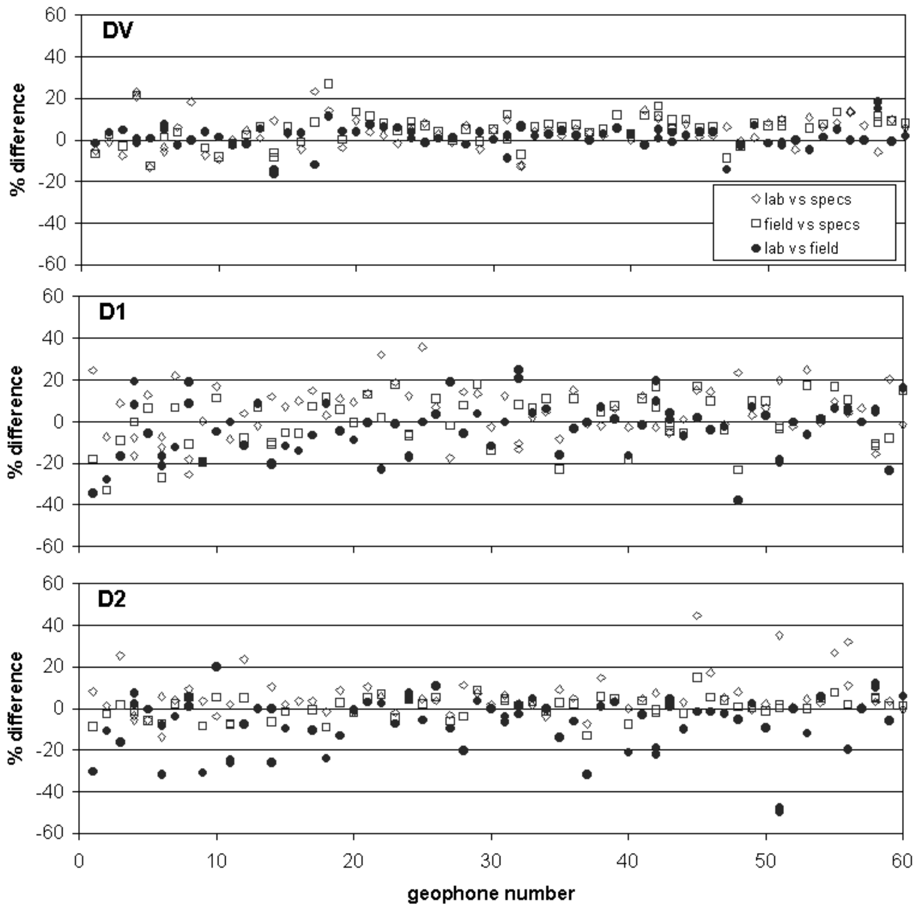

Figure 6: Percent differences in the damping (D) of the L-22 geophones. Symbols and plots as in figure 4.

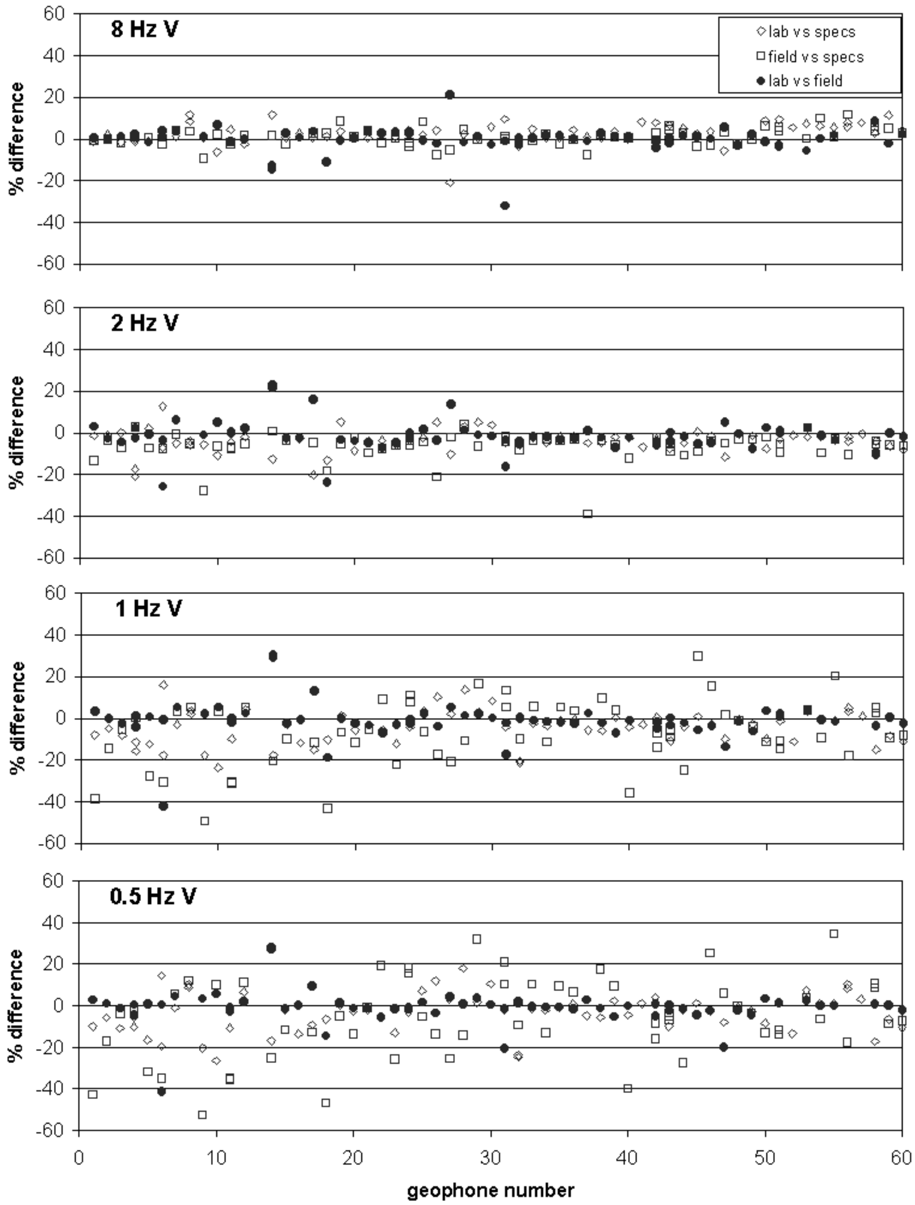

Figure 7: Velocity sensitivity of L-22 geophones, vertical component (V), computed from the results of the calibration tests using equation (1) for frequencies of 8, 2, 1 and 0.5 Hz. Symbols as in figure 4. Note that the differences between the two calibrations (black dots) are generally less than the differences from specification (open symbols), indicating that the two calibrations give similar results.

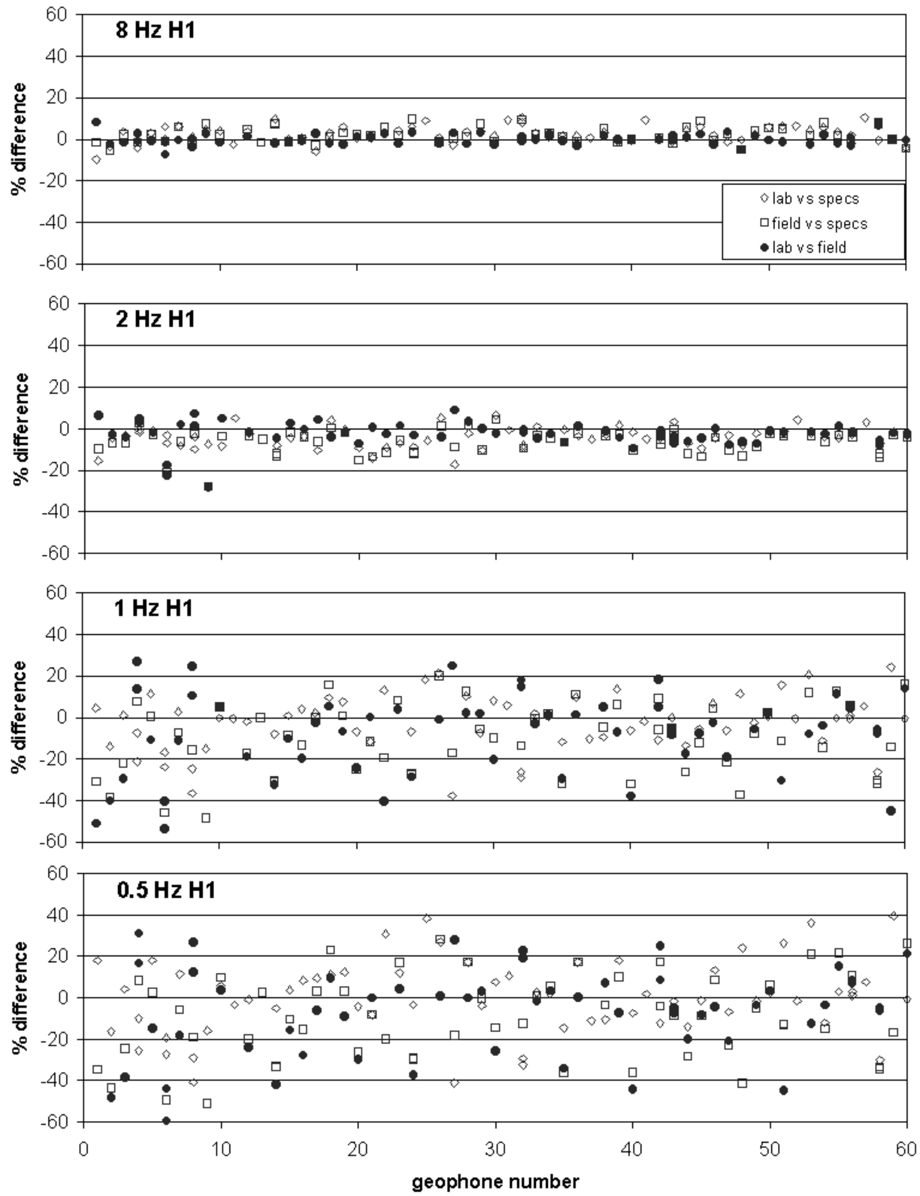

Figure 8: Velocity sensitivity of L-22 geophones, first horizontal component (H1), computed from the results of the calibration tests. Symbols as in Figure 4.

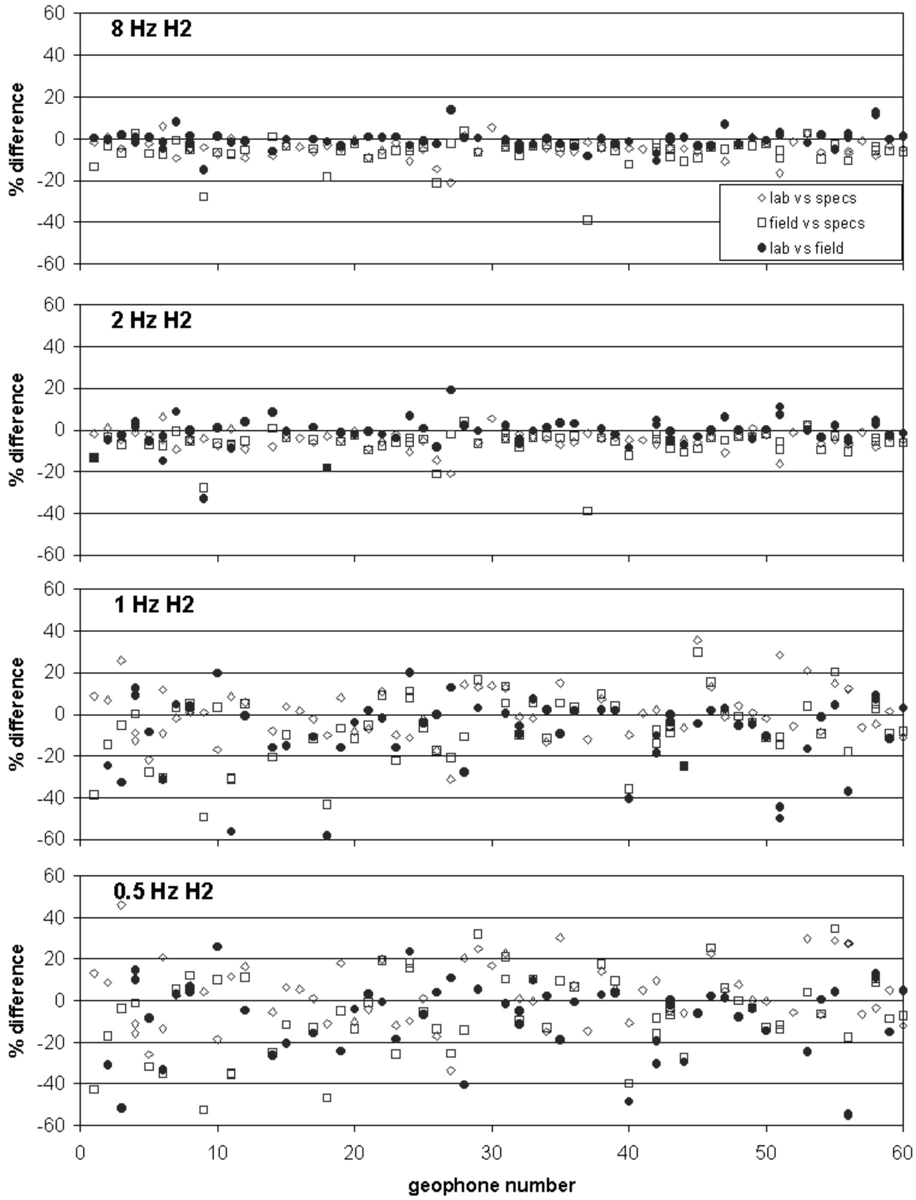

Figure 9: Velocity sensitivity of L-22 geophones, second horizontal component (H2), computed from the results of the calibration tests. Format as in Figure 4.

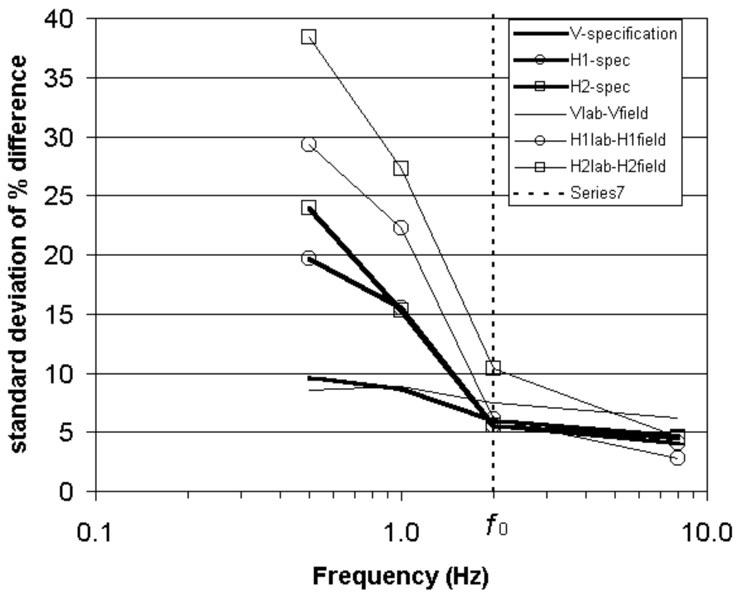

Figure 10: Standard deviations of the differences in velocity sensitivity measured in our calibrations versus the manufacturer's specifications (heavy lines) and between our lab and *in situ* calibrations (light lines). Note that the percent differences increase dramatically below the resonant frequency of 2 Hz, indicating substantial variations in the geophone response.

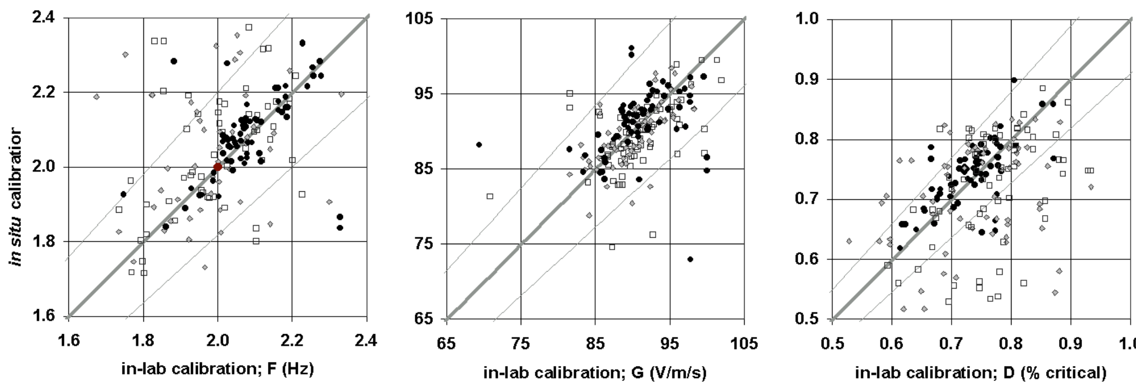

Figure 11: Comparison of the frequency (left), damped generator constant (center) and damping (right) from the *in situ* and laboratory calibrations. Black dots show the vertical component and the gray diamonds and open squares show the horizontal components. Thick line shows equal values and light lines show 10% differences.

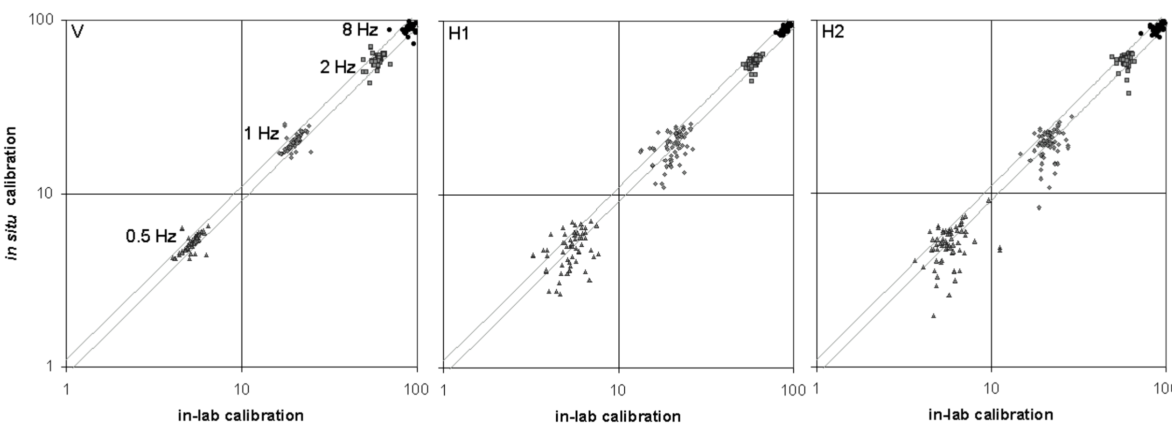

Figure 12: Comparison of geophone velocity sensitivity (in V/m/s) from the *in situ* and laboratory geophone calibrations. The three graphs show the results for the vertical (left) and two horizontal components (center and right). Clusters are calibrations at 0.5, 1, 2 and 8 Hz (labels in left graph). The gray lines delineate differences of ±10% between the two calibrations.